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Beamed Launch Propulsion

Koichi Mori

Abstract

An advanced concept of launch system from ground to orbit, called laser launch system, has been discussed. As a 100-kW-class fiber laser has been developed today, the laser propulsion is now a realistic option for launching microsatellites frequently at very low cost. In this chapter, we shall discuss several unresolved technical problems such as propulsion design and laser beam transmission through atmosphere. It is proved theoretically that high specific impulse higher than 900 seconds is possible in a new conceptual design. On the other hand, the laser beam may be suffered by the atmospheric turbulence when the launch vehicle reaches at altitude higher than 10 km.

Keywords: launch vehicle, laser propulsion, laser, rocket propulsion, wireless power transmission

1. Introduction

In this chapter, we consider the unknown system called laser propulsion. Designing the system is a mixture of various engineering fields, including propulsion engineering, laser engineering, electromagnetic wave engineering, flight dynamics, and control engineering, which are interconnected to each other. The laser propulsion has been studied in the field of the propulsion engineering for more than 50 years. Moreover, the laser propulsion appeared as a gadget in several sci-fi works [1, 2]. (Strangely, in all those works, the laser propulsion is introduced as a technology of aliens rather than an earth-oriented technology. It would reflect that this technology is full of mysterious images.) However, in view of the practical application, few have achieved so far. This is mainly because no laser facilities whose continuous power is sufficiently high have been available. However, in 2010, the world has changed. A 100 kW fiber laser has been commercialized by IPG Photonics Inc. A 100 kW fiber laser facility has been delivered to the NADEX laser R&D Center in Fukui, Japan. We come to the place where we can do genuine experiments of laser propulsion. Surrounding situations are being prepared today. Laser propulsion is one step short of practical application.

As shown in **Figure 1**, in the laser launch system, a vehicle is propelled by transmitting the propulsive energy via laser beam from the ground. Gaining the specific impulse higher than the practical chemical propulsions, the laser propulsion is of the same class of the electric propulsion for spacecraft. At the same time, by leaving the heavy part of the energy source on the ground, the lightweight vehicle on the basis of simple propulsion energy system is realized.

In the following, at first, we are going to consider why the laser propulsion is necessary. For this, we need to consider what kind of launch systems will be required in near future. The conventional rocket technology is in the period of

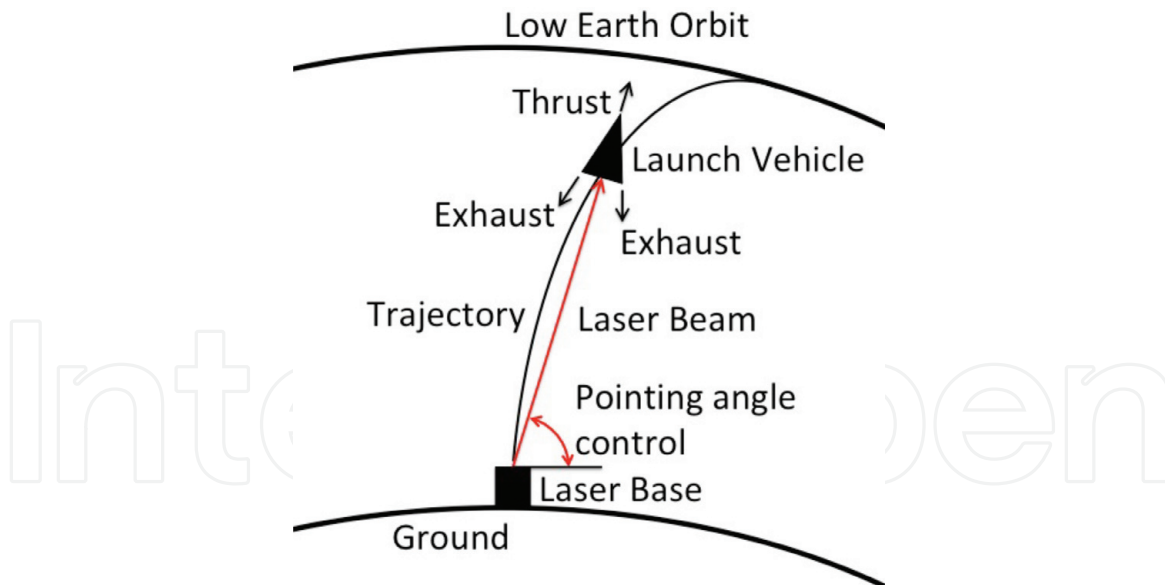


Figure 1.
Laser launch system.

maturity, while the fetal movement for new launch system of high specific impulse that is not limited by the chemical reaction has been ignited. Then, we need to investigate what kind of the laser propulsion system is technologically feasible. Ensuring the foregoing studies of the laser propulsion, we shall consider the practical laser launch system. The technological problems to be solved are numerous. The laser transmission through turbulent atmosphere gives critical problems to the feasibility in the laser launch system although they have been half ignored so far. Solving the numerous technological problems that are necessary to realize the laser launch system is related to the advanced technology such as Starshot project [3], space-based solar power [4], and laser communication in space [5]. Naturally, the space will become familiar by realizing the laser propulsion. Laser propulsion is the technology that is worth challenging.

2. Principles of laser propulsions

Laser propulsion is a variation of the wireless power transfer (WPT) technology, which transfers power remotely using electromagnetic (EM) waves such as microwaves or laser beams. When electric power is necessary at the receiving side, the power of EM waves is transformed to dc current using semiconductors. For the laser propulsion, the power of EM waves is transformed directly into the enthalpy of a working fluid to generate momentum via thermal propulsion mechanisms. This can be called the laser thermal propulsion (LTP). Similar idea would be the laser electric propulsion (LEP) that converts the EM wave power to the dc power to store in the battery once, and then the dc power is used to generate thrust via electric propulsion mechanisms. The LEP is a new idea that allows the storage of the energy on board. However, the heavy weight of the battery would be the bottleneck for the feasibility of this system. Moreover, the LTP will be more energy efficient than LEP because the LEP requires multiple energy conversion processes, which lose the power at each stage. On the other hand, for LTP, it is necessary that the laser beam is always irradiated on the vehicle so that the control mechanisms keep the linkage between a laser source on ground and a fast-moving vehicle. Moreover, it is necessary to keep the vehicle in sight of the laser source so that available flight trajectory of the vehicle is largely limited. Furthermore, the atmospheric perturbation to the

laser beam may be a critical factor in the feasibility study of the LTP. A laser beam is transmitted across turbulent atmosphere for a long distance up to 100 km from ground to space.

There are two kinds of the laser propulsion: repetitive pulse (RP) laser type and continuous wave (CW) laser type. The concept of laser propulsion is first proposed by Kantrowitz in 1971 [7]. His concept was to irradiate the laser beam on the ablator installed on the bottom surface of the vehicle as propellant. At that time, it was unknown how much the momentum can be generated for a certain laser power. The research team led by Kantrowitz first investigated the momentum coupling performances of RP laser propulsion and its physical mechanisms. As a result, the impulse generation mechanisms of laser-supported detonation waves and laser-supported combustion waves have been developed. At the beginning of 2000s, Myrabo invented a new vehicle design called a Lightcraft, which is illustrated in **Figure 2**, to perform first launch demonstrations using a 10-kW-class CO₂ RP laser facility of US Air force [8]. He succeeded in the independent flight of the vehicle without any external guide or support except for the laser beam for the first time in the world. The world record of the flight altitude was 71 m. Through the development of the Lightcraft, Myrabo developed the concept of “beam-riding.” The vehicle must be kept irradiated to generate the momentum all the time of flight. Lightcraft was designed to keep its trajectory along a fixed laser beam, while this is the meaning of the term of beam-riding. When the vehicle position is deviated from the laser beam, the recovery side force is generated to the vehicle to keep the trajectory. His consideration was epoch-making because no previous studies in the laser propulsion have considered the flight dynamics of the vehicle. In the same periods, Sasoh invented the in-tube laser propulsion, which is illustrated in **Figure 3**, and investigated the concept experimentally using a 1-kW-class RP CO₂ laser. A projectile could be accelerated in a tube efficiently due to the confinement effect of the tube wall. In the times of early 2000s, several different types of RP laser propulsion have been invented and investigated experimentally. The concepts of laser propulsion that have been proposed so far are reviewed in the two review papers in detail [9, 10]. From the research team of the author, new laser launch system using “donut-beam,” whose power density has hollow distribution on the cross-sectional plane, higher at peripheral of the cross section than at the center, and a spherical vehicle for stable acceleration has been proposed. This concept is studied in experiments [11] and numerical simulations [12]. Because the concept uses the atmospheric air as propellant, the acceleration performance of vehicle is determined by the aerodynamic drag and the atmospheric air density to be propelled using the laser power. Each concept of

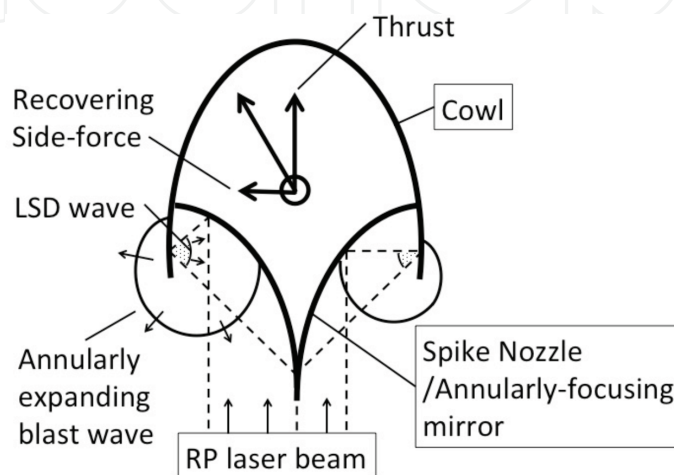


Figure 2.
 Myrabo's Lightcraft.

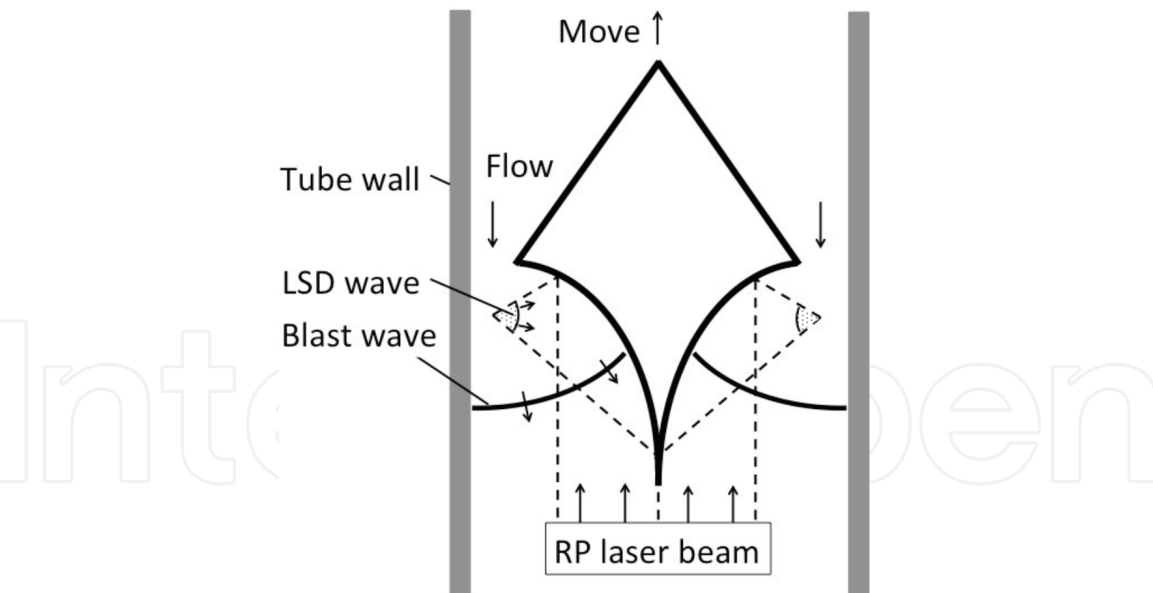


Figure 3.
Sasoh's LITA.

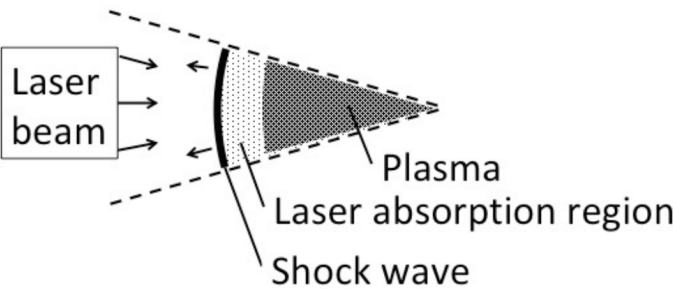


Figure 4.
Laser-supported detonation wave.

RP laser propulsion uses only gaseous propellant or only solid propellant, called the laser ablative propulsion, or the both. The gaseous propellant mostly used is the air atmosphere, and air-breathing propulsion concepts have been studied by many researchers. By focusing an intense laser pulse in the air, a laser-supported detonation wave is generated instantaneously to generate a blast wave around the optical focal point, as illustrated in **Figure 4**. The impulsive thrust is generated as recoil of the blast wave reflection in the nozzle. This method is a variation of the pulse detonation engine (PDE), which generates the thrust via isochoric heating and unsteady gas expansion. The source of the gas expansion, the LSD wave can be generated even in the hypersonic flow, and it can be applied in the air-breathing engines that can operate in hypersonic speeds.

For the CW laser propulsion, only gaseous propellants have been used, because strong momentum coupling from laser ablation requires intense and short laser pulse, and the power density from the CW lasers is too small to be used for the laser ablative propulsion. Moreover, no air-breathing engines have been studied for CW laser propulsion. Two different kinds of rocket were proposed. The laser-sustained plasma (LSP) engines, illustrated in **Figure 5**, use the plasma kept by laser absorption to heat the gaseous propellant running through it [13]. The strong point of this type is high specific impulse more than 1000 seconds because of the high temperature of plasma more than 10,000 K. Mystery remains in plasma stability to the perturbation of the laser power density and its distribution relative to the flows of propellant. Strict optical alignment is necessary for operation. Another kind is heat

exchanger (HX) rocket proposed by Kare, which is illustrated in **Figure 6** [14]. The laser power is converted to the propellant enthalpy via solid heat exchanger so that the specific impulse is limited up to 900 seconds due to the allowable maximum temperature for the heat exchanger. However, the strict optical alignment is not necessary for its operation, and this type is robust to the perturbation to the laser power density and the distribution that is expected during the flight. In the CW laser propulsion, the propellant is heated through the isobaric process, and a propellant pump for an additional compression process is necessary. Hence, the engine for CW laser propulsion is more complicated and then heavier than the RP laser propulsions. This is why no launch test has been accomplished until today.

High-power laser is the first priority to realize the laser launch system (LLS). In all the previous studies, except for Myrabo's campaign, the time-average power of the laser was around a few kilowatt is too low for the practical experiment. As mentioned above, 1 MW laser power is necessary to launch 1 kg payload. Hence, if you want to launch 1-ton payload as in the case of the conventional chemical rockets, you need to prepare 1 GW laser facility. This power is 10^6 times as high as in the previous experiments, and it would be natural to think that even the basic phenomena should be different for such high-power laser in the foregoing experiments. In the previous experiments, it is impossible to generate and maintain continuously a laser-supported detonation wave using CW laser, while it will become possible if one uses the MW or GW-class laser. Once the heating

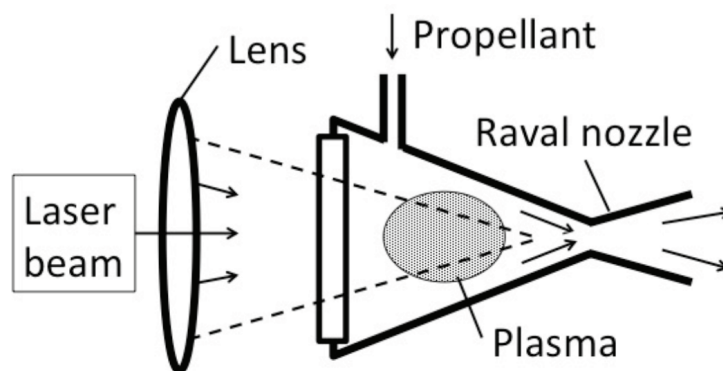


Figure 5.
LSP type CW laser propulsion.

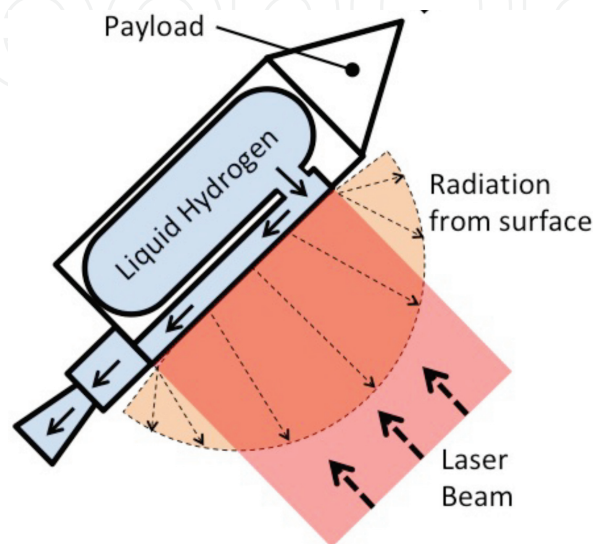


Figure 6.
Heat exchanger rocket.

mechanism is changed, the propulsion design will change. Evolution of super high-power CW laser will induce a new research domain of “high-power CW laser engineering.”

On the other hand, it should be reasonable to assume that the minimum weight of launch vehicle should be heavier than 100 g. As the vehicle becomes smaller, the structural mass ratio is expected to increase to assure the structural strength. Hence, the minimum CW laser power for launch demonstrations should be around 100 kW. Of course, this estimate is quite rough, and the structural design of vehicle, propulsion performance, and trajectory plans should be considered for more detailed feasibility study. The launch system of laser power at 100 kW–1 MW is possible soon. There exists 100 kW fiber laser. It is technically possible to build a 1 MW laser by increasing the number of bundled fibers, and it is the matter of budget. Recently, high-power, energy-efficient, and compact fiber laser has been evolving. CW laser is easier to attain high power rather than RP laser especially in the case of fiber laser. If we could construct the LLS powered by CW laser, the launch demonstration will be completed at early times. As noted above, the design of LLS is the art of the integration in a broad area of engineering field. The relevant field includes propulsion, laser, beam transmission, flight dynamics, and control engineering.

Even after a high-power laser becomes available, a number of the engineering problems are remained. If we could have a proper propulsion system, we should determine the trajectory of a vehicle. The basic guidance law of conventional launch vehicles is the bilinear tangent law. Typical trajectory is illustrated in **Figure 7**. However, for LLS, we need to concern the special issue that a vehicle must stay on the laser beam. Kantrowitz assumed a circular trajectory at which center the laser source is located. It is illustrated in **Figure 8**. For such a trajectory, a good point is that the laser beam can always be irradiated onto the side surface of the vehicle fuselage. Similar trajectory was considered by Escape Dynamics Inc. Possible bad point is the unknown effects of the atmospheric turbulence on the laser beam transmission. Because the atmospheric turbulence is especially strong near the ground, the laser beam should be distorted drastically. This effect gives the degradation of the energy efficiency of the laser beam transmission and the engineering problem to keep a “laser link” between the vehicle and the ground laser facility. Katsurayama et al. proposed a zenith trajectory for LLS as illustrated in **Figure 9**

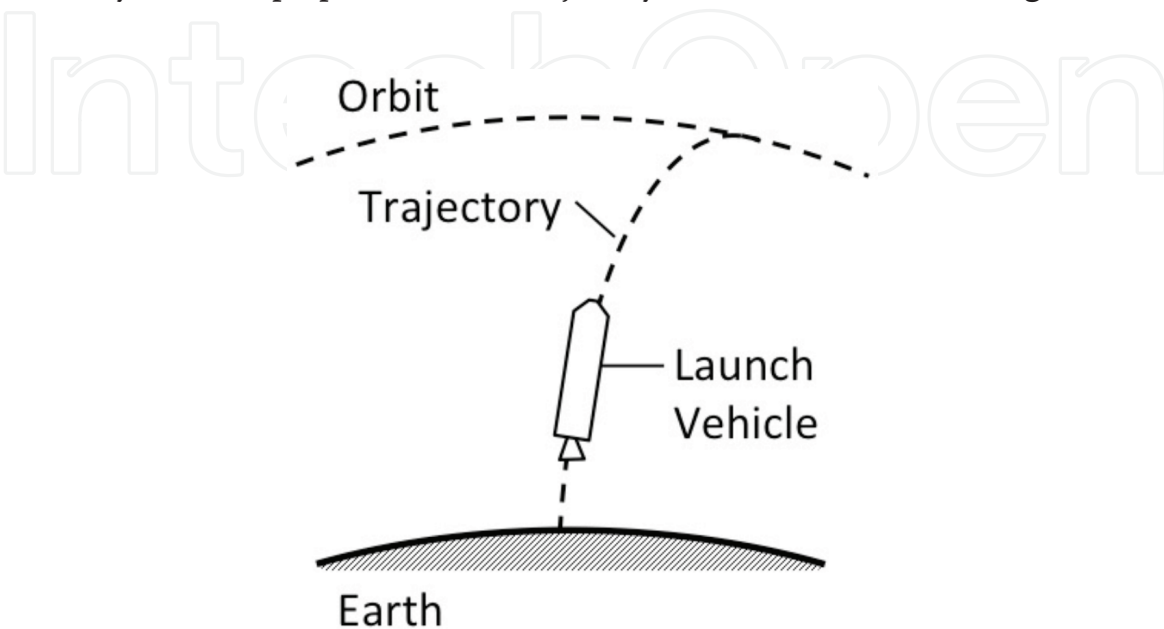


Figure 7.
Typical trajectory of conventional launch vehicles.

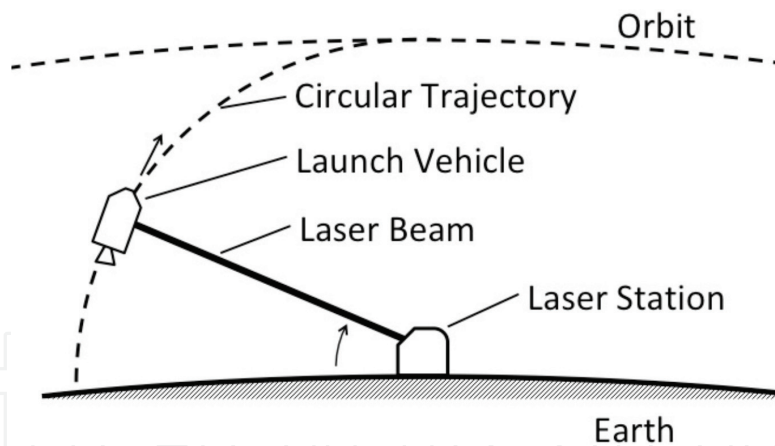


Figure 8.
A circular trajectory concept for laser launch.

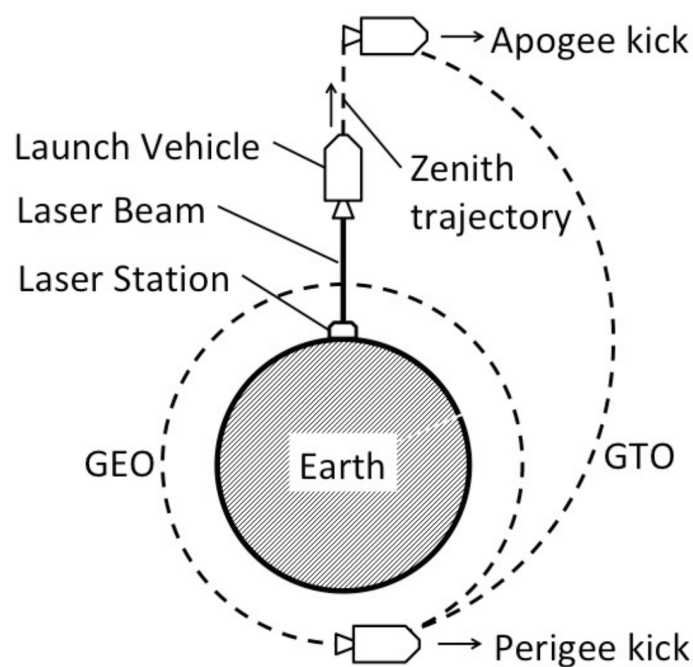


Figure 9.
A zenith trajectory concept for laser launch G.

[15]. The zenith trajectory gives the minimum influence of the turbulence on the beam transmission. A vehicle is transferred via apogee-kick efficiently to the orbit around the earth. They consider using air-breathing engines, which can produce higher velocity increments on horizontal flight, and the optimum trajectory will be possibly determined from the trade-off between the effect of the air turbulence on the laser beam transmission and the air-breathing engine performance. Phipps et al. solved the optimum trajectory for RP laser ablative rocket, without any air-breathing engine, from the ground to the orbit [16]. They commented simply to the effect of the air turbulence on the laser beam propagation. They concluded that the effect of the air turbulence is ignorable to the laser beam whose cross-sectional diameter is smaller than the “seeing size,” which will be explained below; typical value is around 10 cm for the wavelength at 530 nm. They also suggested how to correct the pointing error due to the wave front tilt. More detailed estimation and system design in this aspect is important for the feasibility of LLS.

Moreover, the control mechanisms to keep the laser link between the ground and vehicle are indispensable to maintain the continuous energy supply via laser beam for the operation of the propulsion system. Sasoh’s LITA and Myrabo’s

Lightcrafts are the concepts of the passive way to maintain the laser link. On the other hand, Phipps considered an active control of the optics onboard of the vehicle of the ablative launch system for the first time. Finally, the cooperative control between vehicle and beam pointing will be the natural solution for this issue. For the beam pointing control, the information of the beam position and vehicle position should be resolved precisely. The spatial resolution should be around 1 cm. We need to innovate a high-resolution method to measure vehicle and beam position. After considering these problems, it is clear that the propulsion design and the air turbulence effect on the beam transportation are the root problem.

3. Motivation of laser propulsion

In order to expand the human activities in space, it is indispensable to drastically reduce the cost of transportation from ground to orbit. For an example of today's launch cost, the launch cost for a unit payload mass of the actual rocket of Japan, H-II, to launch a 6 ton payload to geo transfer orbit is around 20,000 \$/kg. Today the price competition is intense so that much of the same is the launch cost value in the USA and EU. Drastic reduction of the launch cost for the unit payload mass has been at stake for a long period. The space shuttle is the first attempt to reduce the launch cost. Shuttle was the first partly reusable launch vehicle. The orbiter was designed reusable to reduce the launch cost by using the orbiter repetitively at a high frequency. However, as it is well-known today, the space shuttle launch system was too huge and complex to reduce the launch cost due to the expensive maintenance. The Space Shuttle Project left the severe lessons for the engineers who still dream to develop a new reusable launch vehicle. Today, the expandable launch vehicles (ELVs) are still major way to the orbit, and the engineers are reducing the cost mainly by the standardization and the simplification. For an example, the next H-III rocket of Japan is claimed to halve the launch cost.

Falcon Heavy produced by SpaceX is a huge rocket that can deliver 26.7 ton to GTO, which is four times as heavy as H-IIA, reducing the launch cost for an unit payload mass around to 6000 \$/kg, which is around one-third of the H-IIA. This is not surprising. On the basis of the statistical data of the ELV developed so far, the launch cost of the ELV has a trend to decrease inversely with the vehicle size [6]. The launch cost for a unit payload mass draws a unique curve decreasing with the payload mass for the same launch mission. Falcon Heavy owes its low price to its large size. It is unclear if the price would continue to decrease with increasing the rocket size, like a huge launch vehicle for the interplanetary transport system designed by SpaceX. For the drastic cost cut, revolutionary breakthrough is necessary to compete the launch market.

To the opposite direction, the unit launch cost naturally increases with the decreasing the payload weight. Recently, R&D of small satellites is very active, and the nanosats (lighter than 10 kg) and picosats (<1 kg) will become in practice soon. Then, the demand for very small launch vehicle (VSLV) at reasonable cost is increasing. Several teams are now developing VLSV using liquid propellant. The Vector Space System Inc. is launching small-sat launch vehicle, which can deliver a 65 kg payload to LEO using liquid propellant rocket using propylene and LOX. The Interstellar Technologies Inc. is launching a gas pressure-pumped liquid propellant rocket called MOMO, while the Rocket Lab Inc. developed electrically pumped liquid rocket engines. In general, liquid propellant offers the specific impulse higher the solid propellant rockets. On the other hand, the liquid propellant rockets tend to

be more complicated than solid rockets partly because the liquid propellant needs to be pressurized and pumped to the combustion chamber of rocket engines. The final price would be determined by the balance between structural complexity and increase in the specific impulse.

This can be explained in more quantitatively as follows. The launch cost of ELV mainly consists of the production cost of the launch vehicle and the propellant cost, if we could ignore the development of the system and the infrastructure maintenance of launch site. We shall start from the Tsiolkovsky rocket equation:

$$\frac{m_{\text{pay}} + m_{\text{st}}}{m_{\text{pay}} + m_{\text{st}} + m_{\text{prop}}} = \exp \left[\frac{\Delta V}{g I_{\text{sp}}} \right] \quad (1)$$

Here, ΔV is the velocity increments required to reach the orbit, I_{sp} is the specific impulse, m_{st} is the structural mass, m_{prop} is the propellant mass, and m_{pay} is the payload mass. We shall define empty mass as $m_{\text{empty}} = m_{\text{st}} + m_{\text{prop}}$. Structural mass ratio ϵ is defined as $m_{\text{st}}/m_{\text{empty}}$. Furthermore, we shall assume simply that the production cost of the vehicle is proportional to m_{st} and the propellant cost is proportional to m_{prop} . Then, the launch cost, C , is proportional to m_{empty} . The constant of proportionality is defined as α . After several mathematical steps of Eq. (1), the launch cost for an unit payload mass is formulated as

$$\frac{C}{m_{\text{pay}}} = \alpha \frac{1 - \exp \left[\frac{\Delta V}{g I_{\text{sp}}} \right]}{\exp \left[\frac{\Delta V}{g I_{\text{sp}}} \right] - \epsilon} \quad (2)$$

From this equation, it is proved that the launch cost for a unit payload mass decreases monotonously with I_{sp} , while it decreases with ϵ . It is effective way to reduce the launch cost by increasing I_{sp} and reducing the vehicle mass. This theoretical result is consistent to the VSLV designs by the ventures. Moreover, in order to ensure the structural strength of VSLV, ϵ increases inevitably as the vehicle size is reduced, increasing the launch cost. Here, we assume the single-stage launch, while the launch cost increases with the number of stages. Unfortunately, even when liquid propellants are used, it is quite difficult to realize the single-stage launch vehicle due to the limitation of chemical rocket I_{sp} less than 460 seconds. Extreme reduction of launch cost can be attained by higher jump of I_{sp} with extremely simplified structure of the vehicle, at a single stage.

This will be attained by using laser propulsion. By using only hydrogen as propellant, I_{sp} can reach 900 seconds, which is limited by the allowable temperature limit of the engine materials, and the hydrogen temperature cannot exceed around 3000 K. The vehicle can be extremely simplified as the energy source is left on the ground. Laser propulsion can launch the payload of around 1 kg with a 1 MW laser facility. The maximum power of the available laser facility is 100 kW today. In principle, it is possible to develop a MW-class laser by bundling the fibers with the price of several tens million US dollars. Once it is developed, massive materials, though just 1 kg at a time, can be launched continuously and on demand to the orbit. The price of the 1 MW-class laser facility is almost the same level of a single launch of H-IIA rocket vehicle. Once a VSLV on demand is realized, the induction effect is expected for the technical breakthrough and the market expansion of small satellites. On the other hand, a GW-class laser facility is necessary to launch a payload of several tons at a time, which is typical launch capability of conventional launch systems. The development of such a huge laser facility will require an extremely large budget, and it would not be easy to realize in near future.

4. A new design of laser propulsion

Then, assuming that a 100-kW-class CW fiber laser is available, we shall consider how to build the LLS. At first, we need to expect the fluctuations of the laser power, the laser beam incident angle, and the cross-sectional distribution. For this reason, the heat exchanger type requires no precise optical alignment of the incident laser beam on the vehicle. Kare's concept of heat exchanger rocket is illustrated in **Figure 6**. This is similar to the microwave rocket concept illustrated by the Escape Dynamics Inc. in 2015. In principle, the nuclear thermal rocket, like NERVA, is a kind of heat exchanger rocket. The specific impulse of a thermal rocket is maximized by using propellant of minimum molecular weight, hydrogen. If the propellant temperature could reach at 3000 K, the specific impulse in vacuum becomes 900 seconds [17, 18]. Nevertheless, Kare's estimation of the proper-specific impulse is around 600 seconds. In this concept, the laser beam is irradiated and absorbed on the side surface of the vehicle fuselage, where the temperature is highest, and the propellant is heated through the heat convection on the inner surface of the fuselage. The temperature of the propellant never exceeds the temperature of the outer surface. Because the maximum temperature of the outer surface of the heat exchanger limits the maximum temperature of the propellant, the specific impulse is limited by the thermal resistance of the materials for the outer surface. Because the atmosphere includes the oxygen, the oxidation resistance is also an important issue for the outer materials. Moreover, a large amount of black-body radiation is emitted from the outer surface and is dissipated in the air as a significant factor of the energy loss. Furthermore, this type of the heat exchanger requires quite narrow flow channel to assure high heat transfer rate, and this causes the significant pressure loss of the propellant in the heat exchanger.

An alternative design of heat exchanger rocket is illustrated in **Figure 10**. We shall consider the zenith angle launch similar to Katsurayama's concept. As mentioned earlier, the zenith angle launch minimizes the effect of the atmospheric turbulence on the laser beam transmission and the complexity of the guidance and control. The vehicle introduces the laser beam of high-power density from the bottom surface of vehicle. Due to the atmospheric turbulence, the laser beam is expanded and deflected. In addition to the propulsion system of high performance (efficient and high specific impulse), precise beam pointing to a small window on the bottom surface of the vehicle is another key issue. A thrust-vectoring gimbal is assumed here for the attitude control. The pointing control and guidance are performed in a cooperative system consisting the propulsion thrust, gimbal, and laser beam optical system on the ground. The vehicle position is always informed onto the ground station. This will be done by the GPS signal from the vehicle or the optical tracking system on the ground or on orbit. On the basis of the information, the beam direction is controlled on the ground. At the same time, the exact position of the laser spot is detected on the vehicle and informed to the ground station. The beam position is adjusted from the ground, while vehicle adjusts its position transverse to the beam direction. Although more detailed analysis and design are necessary, we shall leave this issue for the future work. Before this issue, it is critical to investigate the effect of the atmospheric turbulence on the laser beam propagation through the atmosphere. As mentioned later, the high-frequency fluctuation of the laser beam direction (scintillation) should be critical when the vehicle attains the altitude higher than 10 km. Unfortunately, there is no control technique real-time correction of the scintillation today. The astronomers are taking pictures of stars at short exposure time, by catching the instantaneous image. The real-time correction of the beam direction should be based on the adaptive optics, for which we need to

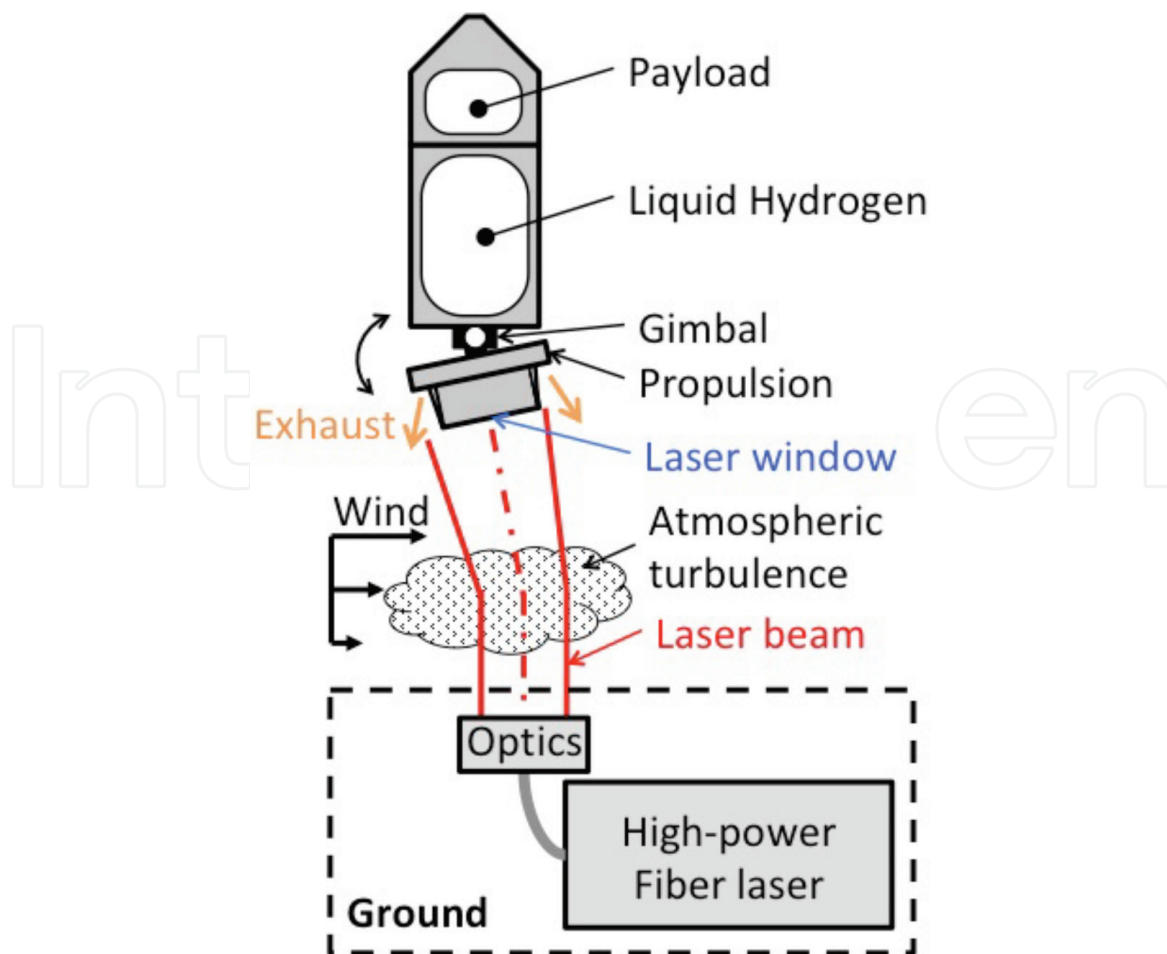


Figure 10.
 Alternative LLS.

detect the atmospheric turbulence on the ray line between the ground station and the vehicle by some means. We need to develop anti-scintillation techniques in the near future. However, for the development of the launch system, we need to move forward step by step. It should be better to start from the aim to a 10 km altitude along the zenith angle trajectory. Myrabo reached at 71 m. The 10 km is a well worthwhile challenge. For the control and guidance techniques, before going to the cooperative control, it is realistic to accomplish more simple method of the active beam-riding flight along a vertical trajectory.

For the propulsion, we shall investigate an externally heated rocket, similar to Kare's concept, using liquid hydrogen as propellant. For the externally heated rocket, the specific impulse is limited by the thermal and oxidation resistance of the high-temperature materials, while the propellant can be selected per request. The propulsion system is illustrated in **Figure 11**. In this new concept, the inside of the engine is separated via glass window from the outside. Porous material is filed inside of the engine. The porous material absorbs the laser power introduced across the window and converts the laser energy to the enthalpy of the hydrogen gas, which passes through the porous material. One feature of the porous heat exchanger is high rate of heat convection and low-pressure loss when using high porosity and high heat-resistance porous material like DONACARBO Felt© Osaka Gas Chemical Inc. shown on the right of **Figure 4**. Because the diameter of carbon fiber is around 10 mm, large surface area and high rate of heat convection are attainable even at high-porosity condition, which leads to the low-pressure loss. Because the heat exchanger is in a close cell filled with the hydrogen, the maximum temperature of

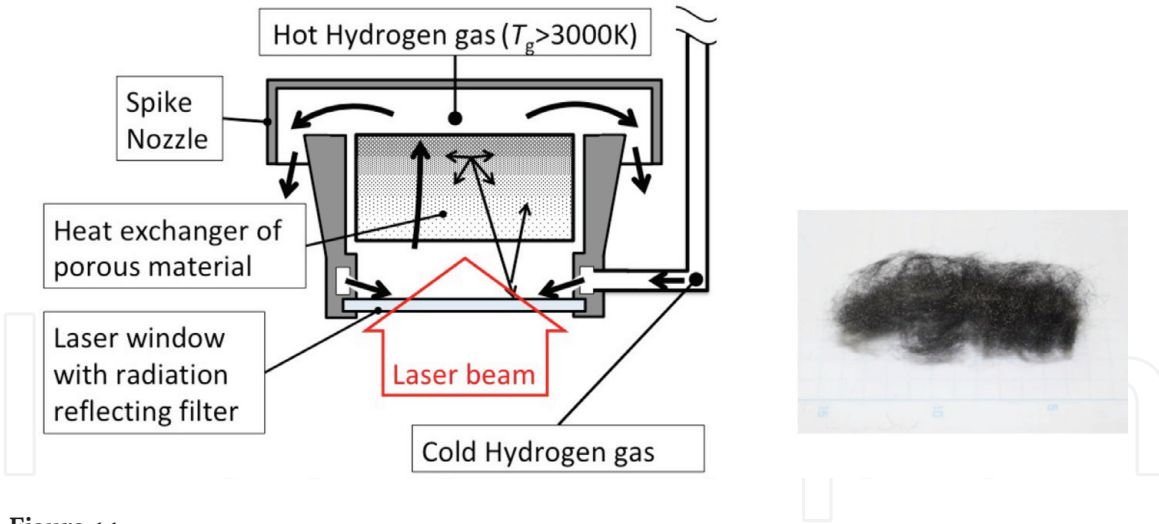


Figure 11.
Schematic of volume absorber-type laser rocket engine.

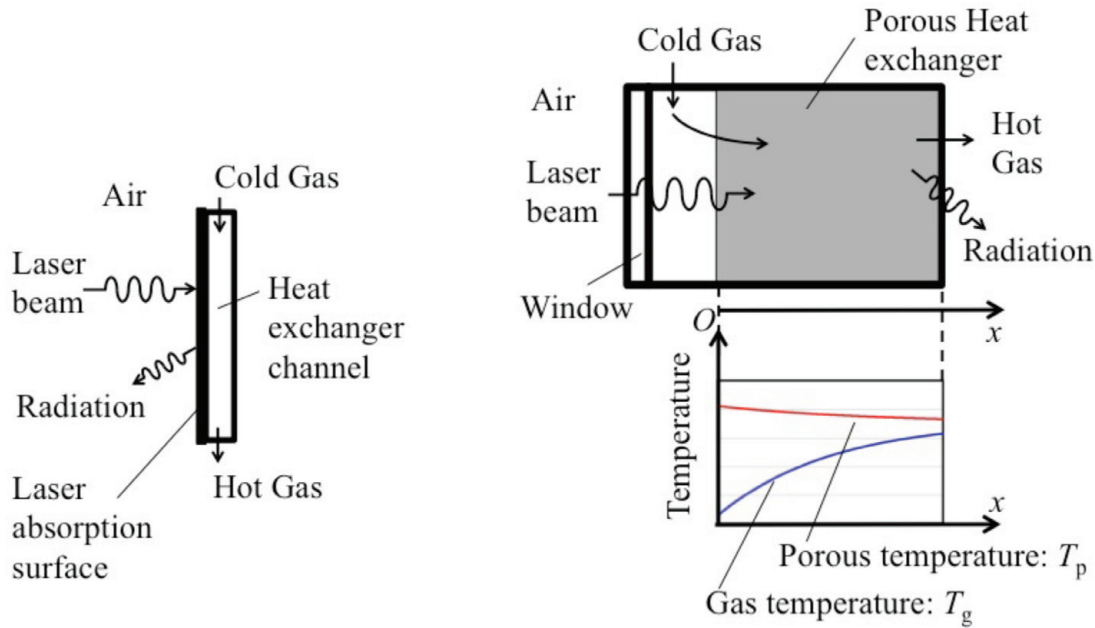


Figure 12.
Surface absorber vs. volume absorber.

the graphite materials will be more than 3000 K. (Sublimation point of graphite under anaerobic condition at one atmosphere pressure lies between 3895 and 4020 K [19].) Another feature of the porous media heat exchanger is the moderate absorption length that can be varied by the bulk size and the porosity of the porous material. This may lead to the reabsorption of the radiation from the high-temperature part of the porous material and the suppression of the energy loss due to radiation. By heating up the hydrogen gas to around 3000 K, the specific impulse in vacuum condition will reach at 900 seconds. In **Figure 12**, the “volume absorber” in the present concept is compared with the conventional Kare’s concept of the so-called surface absorber. We shall consider the theoretical modeling of the volume absorber.

For the energy balance of the bulk material of porous media and the gas past the porous media, we shall consider the one-dimensional model as

$$ha_v(T_p - T_g) + \frac{dI_L}{dx} + q_{\text{rad}} = 0 \quad (3)$$

$$\rho u C_{p,g} \frac{dT_g}{dx} - h a_v (T_p - T_g) = 0 \tag{4}$$

Here, T_p and T_g are the temperature of the bulk material of porous media and the gas, respectively. x is the coordinate inside of the porous media as illustrated in **Figure 12**. ρ is the density of gas. u is the velocity of the gas. $C_{p,g}$ is the specific heat at constant pressure of the gas. h is the volumetric interfacial heat transfer coefficient, for which a number of empirical models have been presented, and is the function of Reynolds number whose standard size is element size of the bulk material of the porous media. For the carbon fiber-based porous media, the standard size should be the diameter of the carbon fiber, which is around 10 μm . When hydrogen is used as working gas, because hydrogen has the largest mean free path among the species at certain pressure, the porous flow features high Knudsen number, and then the analysis could become complicated. The fiber size significantly affects the energy transfer processes. a_v is the specific surface area of porous medium (surface area per unit volume), and q_{rad} is light power irradiated by the black-body radiation from the element surface of porous medium, which is determined on the basis of the Stefan-Boltzmann law. I_L is the laser power density. The scattering of the laser light, the scattering and reabsorption of radiation from high-temperature part, the reflection of radiation on the interface between the porous media and the engine wall, and the heat conduction inside of the porous media have been ignored. In a real engine, the energy efficiency can be enhanced by transforming the radiation to the gas enthalpy. For the heat convection in the porous media, the local thermal equilibrium (LTE) model ($T_g = T_p$) is frequently used. On the other hand, we shall use more general local thermal nonequilibrium (LTNE) model. Actually, the temperature difference between the gas temperature, T_g , and the bulk material temperature, T_p , drives the heat convection. Note that all the variables are calculated in SI unit.

The calculation results for laser power at 100 kW and hydrogen propellant are shown in **Figure 13**. The total temperature and the energy efficiency defined as the fraction of the laser power that is converted to the gas enthalpy are plotted as functions of the incident laser power density, I_{L0} . δT is defined as $I_{L0}/\rho u C_{p,g}$, which is equal to the temperature of the gas without energy loss. On the curve of a constant δT , the mass flux ρu increases as the laser power density, I_{L0} , increases. As is clear from the figure, the energy conversion efficiency increases monotonously with I_{L0} . In order to attain 3000 K, I_{L0} should be larger than 10^9 W/m^2 , which means that the 100 kW laser beam is focused on a spot of the order of 1 cm.

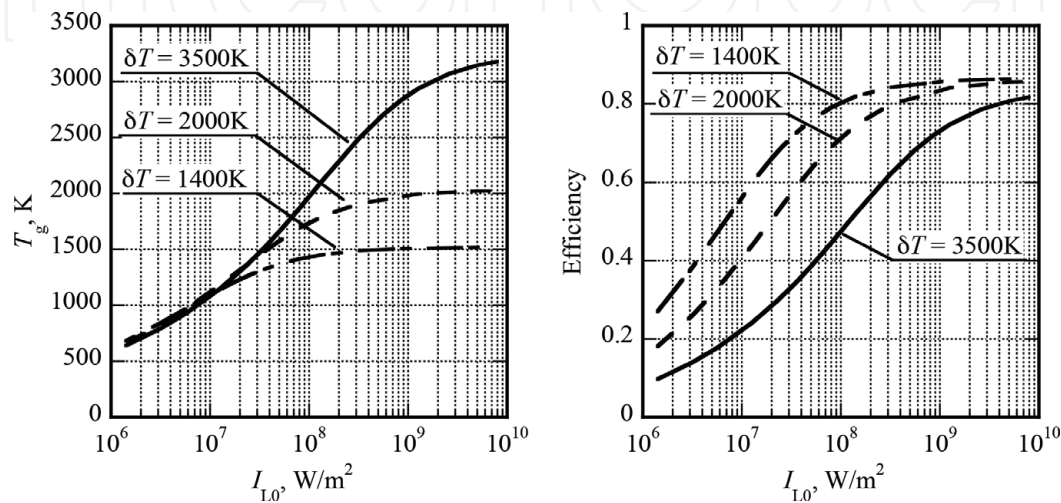


Figure 13.
Result of propulsion model.

Moreover, because the mass flux is quite large, the Reynolds number and the Mach number of the flow into the porous media become 10^2 and 0.3, respectively, which are extraordinarily large numbers for the porous flows. The heat transfer model should be further investigated experimentally.

5. Beam transmission through the atmosphere

The laser beam transmission through the atmosphere is a critical issue for the feasibility of LLS. For the LLS, the laser beam propagates from 0 to 100 km across the atmosphere to point continuously and precisely on a vehicle. The laser beam expands both due to diffraction and atmospheric turbulence. In the studies of the LLS, to the best of author's knowledge, as noted above, only Phipps et al. have considered the atmospheric beam transmission simply using the Fried parameter. Several studies considered the solar power satellite, SPS, using laser beam though there is no systematic study for the beam transmission through the atmospheric turbulence. This is partly because relevant theory has not been fully developed. The light wave propagation through the turbulent atmosphere has been studied in the field of astronomy in terms of the adaptive optics [20]. Only numerical simulations on the basis of the random phase screen method is useful for the exact analyses. To be exact, the atmospheric turbulence depends on local and instantaneous weather conditions. For a particular launch site, the numerical studies and the launch tests are necessary to verify the local effects of the atmospheric turbulence on the laser beam transmission. In some cases, it is necessary to apply the adaptive optics (AO) techniques like the large telescope like Subaru. On the other hand, qualitative discussion is also useful for typical cases, but it is not easy on the basis of numerical simulations. The analytical formula for the effects of the air turbulence on the Gaussian beam was found in 2009 [21]. What is necessary now is to know how and how much the air turbulence can affect the beam propagation. In this section, we shall discuss the impact of air turbulence on the laser beam propagation qualitatively on the basis of recent result in the research field of AO.

In order to attain high-transmission efficiency, the laser spot on the vehicle is adjusted to a proper size. The beam diffraction is regulated using the focusing optics. From the formula of diffraction limit, the minimum spot diameter of a Gaussian beam, d_s , is formulated as a function of the propagated distance z and wavelength λ , the beam quality factor at M^2 , and the beam diameter on the source of beam, ϕ_0 :

$$d_s = 1.2 \frac{z\lambda M^2}{\phi_0} \quad (5)$$

Substituting $z = 100$ km, $\lambda = 1$ μ m, $M^2 = 1.1$ (typical value for fiber lasers), and $\phi_0 = 36$ cm, we get $d_s \sim 37$ cm. This means that a straight beam of 30 cm can be built.

The effect of the atmospheric turbulence on the laser beam propagation is categorized: (1) scintillation, (2) beam expansion, and (3) beam wander. Scintillation is the so-called twinkle of stars. The intensity of the light varies unsteadily at high frequency. Beam expansion means the additional expansion of the beam diameter after propagating on a long path across the atmosphere. Beam wander means the variation of the center of the laser beam axis on the cross-sectional surface. This is induced by the additional angular deflection of the laser beam due to the air turbulence. These effects are originated from the fluctuation in the deflection index distributed in the atmosphere; described using the structure constant of

deflection index C_n^2 . C_n^2 is the function of the altitude, depending on the local weather condition. Since it is sensitive to the instantaneous perturbation as the passing of an aircraft, it is not easy to predict C_n^2 precisely in general cases. Here, we shall choose well-known HV 7/5 model for the altitude distribution of C_n^2 [20].

Fried parameter (or called coherence length or seeing size) r_0 is defined by integrating C_n^2 along the beam direction as

$$r_0 = \left[0.423k^2 \sec(\beta) \int_0^L C_n^2(z) dz \right]^{-3/5} \quad (6)$$

Here, k is the wave number of the laser beam, $\sec$ is the secant (trigonometric function), β is the zenith angle, and L is the propagation distance. When a laser beam is transmitted from the ground to space, r_0 is the maximum beam diameter on the ground for the diffraction limited focusing in space. Even when the beam diameter is larger than r_0 , the spot diameter on space object is larger than the diffraction limit of r_0 . Hence, it is useless to increase the beam diameter on the ground larger than r_0 . Fried parameter equals to the typical size of the turbulence. Its typical value is around 10 cm for the visible light around for $\lambda = 500$ nm. Because $r_0 \propto \lambda^{1.2}$, it is around 20 cm for $\lambda = 1$ μ m. For the flatness of the wave front, isoplanatic angle θ_0 is defined as

$$\theta_0 = \left[2.91k^2 \int_0^L C_n^2(z) z^{5/3} dz \right]^{-3/5} \quad (7)$$

The typical value for the visible light ($\lambda = 500$ nm) is 7 μ rad, and considering $\theta_0 \propto \lambda^{1.2}$, typical value is 16 μ rad for $\lambda = 1$ μ m. In HV 7/5 model, the altitude distribution of C_n^2 is formulated as follows taking r_0 and θ_0 as major parameters:

$$C_n^2(z) = 5.94 \cdot 10^{-23} z^{10} e^{-z} \left(\frac{W}{27} \right) + 2.7 \cdot 10^{-16} e^{-\frac{2z}{3}} + A e^{-10h} \quad (8)$$

Here, z is the altitude from sea level [km], and h is the altitude from the beam source [km]. When the laser beam is emitted from sea level, $z = h$ as assuming in the following. The unit of $C_n^2(z)$ is $m^{-2/3}$. W and A are the constants that represent the atmospheric condition, formulated using (r_0, θ_0) as

$$W = 27 \sqrt{75\theta_0^{-5/3} \lambda^2 - 0.14} \quad (9)$$

$$A = 1.29 \cdot 10^{-12} r_0^{-5/3} \lambda^2 - 1.61 \cdot 10^{-13} \theta_0^{-5/3} \lambda^2 - 3.89 \cdot 10^{-15} \quad (10)$$

Here, the units of r_0 , θ_0 , and λ are cm, μ rad, and μ m. As shown in **Figure 14**, the typical value of C_n^2 is $10^{-15} m^{-2/3}$ near the ground and is reduced sharply to $10^{-17} m^{-2/3}$ at altitude of 10 km. Then, it becomes almost constant. For the laser beam propagation from the ground to the sky, the atmospheric turbulence has significant impact at altitude lower than 10 km. In the actual atmosphere, the atmospheric boundary layer, typically lower than 2 km, is quite effective to the fluctuations in the laser beam. On the other hand, the conditions in the boundary layer depend on the local landform and are time-varying even in 1 day. This complexity in atmospheric boundary layer makes C_n^2 unpredictable. According to Ref. [21], beam expansion of a Gaussian beam δw is formulated as

$$\delta w^2 = \frac{128}{5} (0.545 C_n^2(z))^{6/5} k^{2/5} z^{11/5} \delta z \quad (11)$$

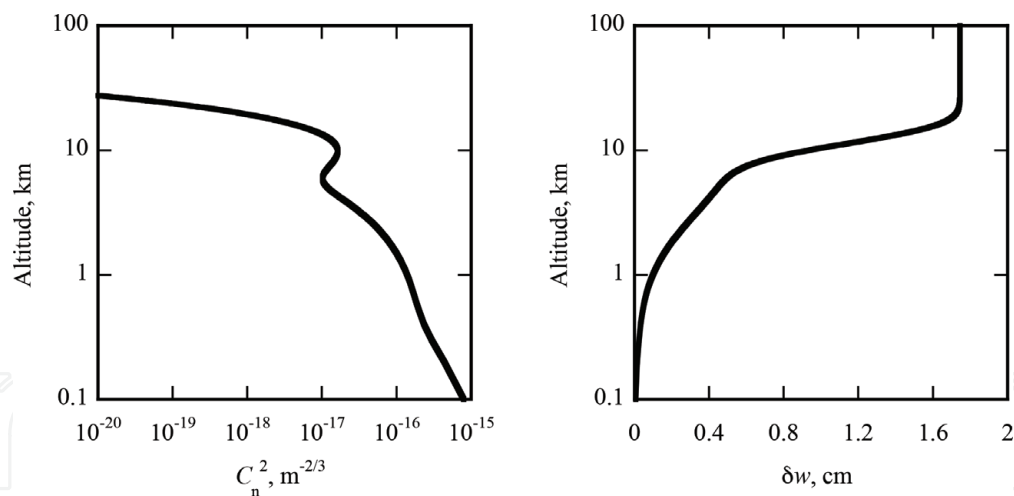


Figure 14.
Examples of C_n^2 and δw for $\lambda = 1 \mu m$, $\theta_o = 16.1 \mu rad$, and $r_o = 23.0 cm$.

$\lambda (\mu m)$	$\phi_o (cm)$	$r_o (cm)$	$\theta_o (\mu rad)$	$\delta\alpha (\mu rad)$	$\delta w (cm)$
0.5	10	10	7	3.0	2.0
1	10	23	16	3.0	1.7
10	10	364	254	3.0	1.1

Table 1.
Beam expansion and wondering at altitude of 100 km.

Moreover, the angular fluctuation due to the beam wondering is formulated as

$$\delta\alpha^2 = 0.364 \left(\frac{\phi_o}{r_o} \right)^{5/3} \left(\frac{\lambda}{\phi_o} \right)^2 \tag{12}$$

As shown in **Figure 14**, δw saturates at the altitude around 10 km.

The results are summarized in **Table 1**. The beam diameter on the ground is assumed 10 cm. The increment of the beam diameter δw is 1.7 cm (around 17%) at the altitude of 100 km. This should be regulated using the optics on the ground. The beam wondering is around 3 μrad . This means the beam position is deflected by 30 cm at the altitude of 100 km. Because the beam diameter is 10 cm and then the size of the beam-receiving surface on the vehicle is almost same, the fluctuation of the beam location at 30 cm is quite large. This fluctuation varies typically at a frequency of 1 kHz. Without any correction to the beam wondering, the thrust cannot be generated at altitude of the order of several tens kilo-meter. On the other hand, the beam wondering should be ignorable in the demonstration of launch up to the altitude of 1 km. Both r_o and θ_o increase with λ . Consequently, although δw decreases slightly with λ , $\delta\alpha$ is constant.

6. Summary

It is clear that we need to develop a launch system of high specific impulse to expand our universe. Laser launch system (LLS) is a promising candidate that can generate the specific impulse higher than 900 seconds. As a 100-kW-class fiber laser has been developed today, actual launch to the orbit will happen in near future. In this chapter, we looked around the technical problems and tried some analyses for the propulsion performance and the atmospheric turbulence effect on

the laser beam transmission. The latter problem will become important in the near future when the laser launch vehicle can reach the altitude higher than 10 km. This problem is linked with the methodologies for the guidance and control of vehicle. Future studies will clarify the design features and technical problems of LLS in more detail.

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